

Effect of Different Rotor Structures on Electromagnetic Vibration of Single-Phase Permanent Magnet Reluctance Motors

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In recent years, single-phase permanent magnet reluctance motors (PMRMs) have attracted much attention in industry, aerospace and other fields, due to their advantages such as low cost, simple structure, and the introduction of permanent magnets to enhance torque density. However, the torque pulsation, electromagnetic vibration, and noise problems associated with the double salient structure are generally regarded as the major drawbacks of this type of motor. This paper comparatively investigates the electromagnetic vibration characteristics of single-phase PMRMs with different topologies. The radial force models of different rotor structures are analyzed, and the coupling mechanism between radial force and vibration of single-phase PMRMs is explored through the establishment of a multi-physical field coupling model. Vibration experiments of prototypes with different rotor structures under different working conditions are conducted to verify the theoretical analysis.

Index Terms—Single-phase permanent magnet reluctance motors (PMRMs), different rotor structures, electromagnetic vibration, acoustic noise.

I. INTRODUCTION

With the growing demand for high-performance drive technology in industrial, aerospace, and other fields, single-phase reluctance motors (RMs) have become a research hotspot in recent years due to their simple structure, robustness, low cost, and other excellent characteristics [1], [2]. Single-phase RMs is classified into permanent magnet (PM) excitation, electric excitation, and hybrid excitation due to their different excitation methods. To improve the power density under the electric excitation method, a single-phase PMRM with a low-cost ferrite PM replacing the excitation winding is designed. Combined with an asymmetric rotor structure design, it greatly improves the starting performance at non-uniform air gaps [2]. The unique double salient structure of PMRMs can introduce serious vibration and acoustic noise problems. In [3], the vibration of a single-phase PMRM is suppressed by reducing the low harmonic amplitude through a dual stator and dual rotor structure. In this paper, single-phase PMRM is taken as the research object to study the effects of different rotor topologies on its vibration and acoustic noise. A radial force analysis model of single-phase PMRM is established. Establish the multi-physics field coupling model of different rotor topologies. Prototypes with different rotor structures are fabricated for vibration experiments to reveal the effects of different rotor topologies on the electromagnetic vibration of single-phase PMRMs.

II. RADIAL FORCE ANALYSIS

The magneto motive force (MMF) produced by the PM in the stator can be expressed as

$$F_r(\theta, t) = \sum_{v=1,3,5,\dots} F_{rv} \cos(v \frac{Z_1}{2} \theta + \frac{\pi}{2}) \quad (1)$$

where F_{rv} is the amplitude of the v th harmonic of the MMF, and Z_1 is the stator tooth number. The air-gap permeance can be written as

$$\lambda(\theta, t) = \Lambda_0 \Lambda_s(\theta) \Lambda_r(\theta, t) \quad (2)$$

where $\lambda(\theta, t)$ is the total permeance function taking into account the stator and rotor slotting effect. Λ_0 is the air gap magnetic permeability without considering the slot of the stator and rotor. $\Lambda_s(\theta)$ is the permeance function for stator slotting, and $\Lambda_r(\theta, t)$ is the permeance function for rotor slotting.

The radial air gap flux density generated by PMs $B_r(\theta, t)$ can be expressed as

$$\begin{aligned} B_r(\theta, t) &= F_r(\theta, t) \times \lambda(\theta, t) \\ &= \sum_{v=1,3,5,\dots} F_{rv} \Lambda_0 \cos(v \frac{Z_1}{2} \theta + \frac{\pi}{2}) \times [\Lambda_{s0} + \sum_{l=1,2,3,\dots} \Lambda_{sl} \cos(l Z_1 \theta)] \\ &\quad \times [\Lambda_{r0} + \sum_{m=1,2,3,\dots} \Lambda_{rm} \cos(m Z_2 \theta - m \omega t)] \end{aligned} \quad (3)$$

where Z_2 is the rotor tooth number. The radial force, based on the Maxwell stress and ignoring the tangential component of the air-gap magnetic density, can be written as

$$p_r(\theta, t) = \frac{B_r^2(\theta, t) - B_t^2(\theta, t)}{2\mu_0} \approx \frac{B_r^2(\theta, t)}{2\mu_0} \quad (4)$$

where B_r and B_t are the radial and tangential components of the air-gap magnetic density, respectively, and μ_0 is the vacuum permeability. Table I shows the radial force harmonics generated by the PM.

TABLE I
RADIAL FORCE HARMONICS GENERATED BY PM

Source	Order	Frequency
PM	$aZ_1/2$	0
PM & Rotor slot	$aZ_1/2 \pm bZ_2$ & $aZ_1/2 \pm mZ_2$	bf_e
PM & Stator slot	$(a/2 \pm c)Z_1$ & $(a/2 \pm l)Z_1$	0
PM & Stator slot & Rotor slot	$(a/2 \pm c)Z_1 \pm bZ_2$ & $(a/2 \pm l)Z_1 \pm bZ_2$	bf_e
Stator slot & Rotor slot	$(a/2 \pm l)Z_1 \pm mZ_2$ & $(a/2 \pm c)Z_1 \pm mZ_2$	mf_e

Where $a=v_1 \pm v_2$, $b=m_1 \pm m_2$, $c=l_1 \pm l_2$. When the spatial order is a multiple of 8, the radial force density is mainly an even harmonic in time. When the spatial order is not a multiple of 8,

the radial force density is mainly odd harmonic in time. The MMF generated by the armature current in a single-phase armature winding can be obtained

$$F_c(\theta, t) = \sum_{\kappa=1,3,5,\dots}^{\infty} \sum_{\nu=1,3,5,\dots}^{\infty} F_{\nu\kappa} \cos(\kappa \frac{Z_1}{2} \theta - \nu \omega_1 t - \theta_1) \quad (5)$$

where

$$F_{\nu\kappa} = \frac{8N_c I_0}{\pi^2 \kappa \nu} \sin \frac{\nu Z_2 \alpha}{2}, \kappa, \nu = 1, 3, 5, \dots \quad (6)$$

where $F_c(\theta)$ denotes the spatial distribution of the MMF, and N_c is the number of armature winding turns. I_0 is the armature current magnitude. θ is the coil's spatial position electrical angle.

Fig. 1 compares the 0th-order radial force harmonic contents corresponding to four different rotor structures. The results indicate that the segmented rotor effectively reduces the low-frequency harmonic content of the radial force compared to the other rotor configurations. It can be seen that the radial force harmonic amplitudes of different rotor structures all appear in even frequencies, corroborating the theoretical analysis presented in this investigation.

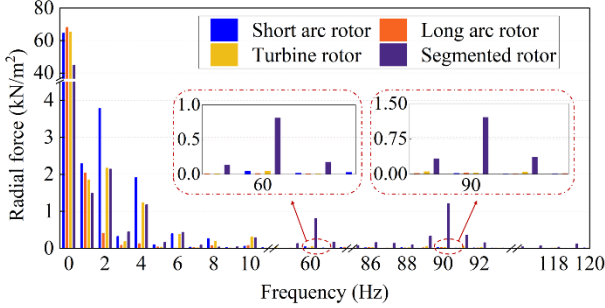


Fig. 1. Radial force harmonics of order 0 for different rotor configurations.

III. VIBRATION SIMULATION AND ANALYSIS

A multi-physical field model was established to calculate the vibration characteristics of its single-phase PMRM and analyze its electromagnetic vibration. The modal test of the stator core is shown in Fig. 2. The modes are shown in Table II.

TABLE II
MODAL FREQUENCY COMPARISON

Model number	2	3	4
Simulated	1475 Hz	2947 Hz	4797 Hz
Measured	1410 Hz	3097 Hz	4817 Hz
Relative error	4.41 %	5.09 %	0.42 %

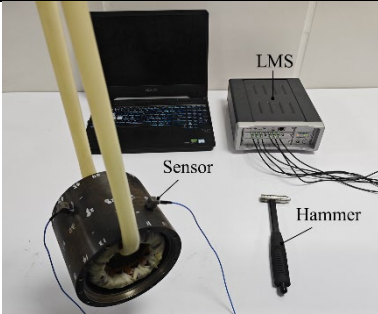


Fig. 2. Modal test configuration for stator core.

IV. VIBRATION EXPERIMENT ANALYSIS

To compare the differences in electromagnetic vibration of single-phase PMRMs with different rotor topologies. Four

prototypes with different rotor structures were fabricated for vibration testing. Fig. 3 shows the experimental platform of the PMRM. Fig. 4 shows the vibration and acoustic noise of the PMRM at different rotational speeds for the turbine rotor topology. It can be seen that a vibration peak occurs near 1475 Hz in the 2nd-order mode. Acoustic noise grows with increasing rotational speed.

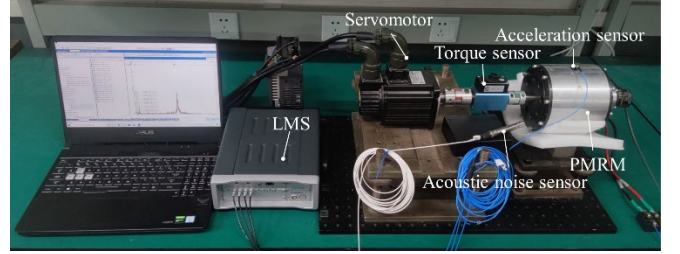


Fig. 3. Vibration experiment platform.

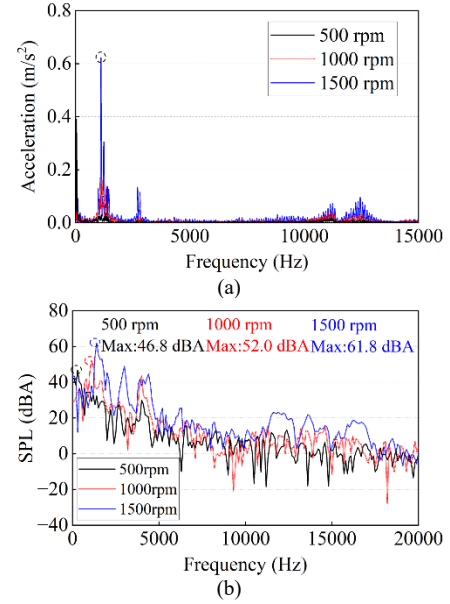


Fig. 4. Vibration and acoustic noise at different speeds. (a) Vibration. (b) Acoustic noise.

V. CONCLUSION

This paper analyzes and compares the vibration and acoustic noise of a single-phase PMRM across various rotor topologies and their underlying causes. It investigates the differences in the radial force mechanisms of different rotor structures and verifies the effects of these rotor structures on the vibration and acoustic noise of the single-phase PMRM under various operating conditions through prototype experiments.

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